The Rio Grande Rift

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The Rio Grande, one of the major rivers of the arid southwestern United States, arises in southern Colorado and flows through New Mexico to Texas. Here, marking the border with Mexico, it turns southeastward toward Big Bend and, eventually, the Gulf of Mexico. The topographic trough along which the river flows from Colorado to Big Bend, part of which is shown in Figure 1, is the expression of a major continental rift, a region of the earth where the lithosphere—the outer, rigid layer of the earth comprised of the crust and uppermost mantle—is being stretched apart.

An area where the earth's lithosphere is being pulled apart provides information about basic geological processes

The earth's lithosphere is divided into segments called plates. Existing plates are ruptured and pulled apart and new plates formed by the process of rifting. Rifts breaking continental crust are referred to as continental rifts. Ocean basins begin as continental rifts, although not all continental rifts evolve into oceans. Those rifts that did not or have not yet become oceans, such as the Rio Grande, preserve a record of the early stages of plate separation, which is overprinted by later processes in those rifts that become oceans. New crust is formed in continental rifts, and old crust is modified. Continental rifts are potential sites of hydrocarbon reserves, geothermal resources, and mineral deposits. They are also places of significant earthquake hazard.

The potential benefits and hazards to society, as well as the desire to understand better these fundamental features of the earth's lithosphere, provide the impetus to study the process of rifting. The Rio Grande rift is a classic continental rift in many of its features, giving us an opportunity to study major processes of crustal evolution and upper mantle structure and dynamics. It is also unique in some features of its development compared with other continental rifts. These differences from other rifts yield important insights into the processes of lithospheric extension.

The Rio Grande rift is part of a broad region of the western United States, known as the Basin and Range province from its physiography of isolated mountain ranges and sediment-filled valleys (shown in Fig. 2), that has undergone extension during the last 30 million years (Eaton 1982). The geological events shaping this region are the result of a unique combination of tectonic events along the western margin of North America.

Initial stretching occurred in a tectonic setting very different from the present. For more than 100 million years prior to extension, the tectonics of the region was dominated by subduction—the process by which one lithospheric plate is deflected beneath another—of the Farallon plate beneath the North American plate to the east, as shown in Figure 3. The rigid plates, which are typically more than 100 km thick, move on a plastic region of the mantle containing a few tenths of a percent of melt. This partially molten zone, extending to depths of possibly 200 km, is called the asthenosphere. The mantle below the asthenosphere is solid, though ductile and capable of slow convection. Subduction proceeded at a relatively modest rate—50 to 110 km per million years. However, for reasons not yet well understood, the rate of subduction increased between 40 and 75 million years ago to 150 km per million years, resulting in flattening of the subducting plate and in greatly increased coupling with the base of the overriding plate (Engebretson et al. 1984). The effects of this coupling—mountain building and thickening of the crust (Bird 1984)—spread inland as far as present-day Wyoming, Colorado, New Mexico, and Texas.

Subduction slowed abruptly about 40 million years ago, and as a result, compressive stress in the lithosphere decreased. A period of widespread volcanism followed, lasting until about 20 million years ago in some regions, during which the lithosphere was thermally weakened by extensive and repeated invasion of melts from beneath. Beginning about 30 million years ago, a major phase of extensional deformation occurred throughout much of the region, resulting perhaps from the decreased rate of subduction. Broad basins formed bounded by low-angle faults, the orientations of which were typically oblique to the present-day structures. Taking place while subduction was still in progress, this

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nature-nurture problem. In *Development and Evolution of Behavior*, ed. L. R. Aronson, E. Tobach, D. S. Lehrman, and J. S. Rosenblatt, pp. 17–52. W. H. Freeman.

9. E. Mayr. 1961. Cause and effect in biology. *Science* 134:1501–06.
10. N. Tinbergen. 1963. On aims and methods of ethology. *Zeitschrift für Tierpsychologie* 20:410–33.
11. P. W. Sherman and M. L. Morton. 1984. Demography of Belding's ground squirrels. *Ecology* 65:1617–28.
12. K. E. Holekamp. 1984a. Natal dispersal in Belding's ground squirrels *(Spermophilus beldingi)*. *Behav. Ecol. Sociobiol.* 16:21–30.
13. P. W. Sherman. 1977. Nepotism and the evolution of alarm calls. *Science* 197:1246–53.
14. P. W. Sherman. 1981a. Kinship, demography, and Belding's ground squirrel nepotism. *Behav. Ecol. Sociobiol.* 8:251–59.
15. G. R. Michener. 1983. Kin identification, matriarchies, and the evolution of sociality in ground-dwelling sciurids. In *Recent Advances in the Study of Mammalian Behavior*, ed. J. F. Eisenberg and D. G. Kleiman, pp. 528–72. Am. Soc. Mammal.
16. C. H. Phoenix, R. W. Goy, A. A. Gerall, and W. C. Young. 1959. Organizing action of prenatally administered testosterone propionate on the tissues mediating mating behavior in the female guinea pig. *Endocrinology* 65: 369–82.
17. K. E. Holekamp, L. Smale, H. B. Simpson, and N. A. Holekamp. 1984. Hormonal influences on natal dispersal in free-living Belding's ground squirrels *(Spermophilus beldingi)*. *Hormones and Behavior* 18:465–83.
18. E. Adkins-Regan. 1981. Early organizational effects of hormones: An evolutionary perspective. In *Neuroendocrinology of Reproduction*, ed. N. T. Adler, pp. 159–228. Plenum Press.
19. K. E. Holekamp. 1986. Proximal causes of natal dispersal in Belding's ground squirrels *(Spermophilus beldingi)*. *Ecol. Monogr.* 56: 365–91.
20. S. Pfeifer. 1982. Disappearance and dispersal of *Spermophilus elegans* juveniles in relation to behavior. *Behav. Ecol. Sociobiol.* 10:237–43.
21. F. S. Dobson. 1979. An experimental study of dispersal in the California ground squirrel. *Ecology* 60:1103–09.
22. J. Moore and R. Ali. 1984. Are dispersal and inbreeding avoidance related? *Animal Behav.* 32:94–112.
23. A. E. Pusey and C. Packer. 1987. The evolution of sex-biased dispersal in lions. *Behaviour* 101:275–310.
24. A. Cockburn, M. P. Scott, and D. J. Scotts. 1985. Inbreeding avoidance and male-biased natal dispersal in *Antechinus* spp. (Marsupialia: Dasyuridae). *Animal Behav.* 33:908–15.
25. J. A. King. 1984. Historical ventilations on a prairie dog town. In *The Biology of Ground-dwelling Squirrels*, ed. J. O. Murie and G. R. Michener, pp. 447–56. Univ. of Nebraska Press.
26. W. M. Shields. 1982. *Philopatry, Inbreeding, and the Evolution of Sex.* State Univ. of New York Press.
27. P. J. Greenwood, P. H. Harvey, and C. M. Perrins. 1978. Inbreeding and dispersal in the great tit. *Nature* 271:52–54.
28. J. L. Hoogland. 1982. Prairie dogs avoid extreme inbreeding. *Science* 215:1639–41.
29. K. Ralls, P. H. Harvey, and A. M. Lyles. 1986. Inbreeding in natural populations of birds and mammals. In *Conservation Biology: The Science of Scarcity and Diversity*, ed. M. E. Soulé, pp. 35–56. Sinauer.
30. P. M. Waser and W. T. Jones. 1983. Natal philopatry among solitary mammals. *Q. Rev. Biol.* 58:355–90.
31. P. W. Sherman. 1981b. Reproductive competition and infanticide in Belding's ground squirrels and other animals. In *Natural Selection and Social Behavior*, ed. R. D. Alexander and D. W. Tinkle, pp. 311–31. Chiron Press.
32. A. E. Pusey and C. Packer. 1986. Dispersal and philopatry. In *Primate Societies*, ed. B. B. Smuts, D. L. Cheney, R. M. Seyfarth, R. W. Wrangham, and T. T. Struhsaker, pp. 250–66. Univ. of Chicago Press.
33. W. P. Luckett and L. J. Hartenberger, eds. 1985. *Evolutionary Relationships among Rodents.* Plenum Press.
34. D. J. Hafner. 1984. Evolutionary relationships of the nearctic Sciuridae. In *The Biology of Ground-dwelling Squirrels*, ed. J. O. Murie and G. R. Michener, pp. 3–23. Univ. of Nebraska Press.
35. K. E. Holekamp. 1984b. Dispersal in ground-dwelling sciurids. In *The Biology of Ground-dwelling Squirrels*, ed. J. O. Murie and G. R. Michener, pp. 297–320. Univ. of Nebraska Press.
36. M. G. Garrett and W. L. Franklin. 1988. Behavioral ecology of dispersal in the black-tailed prairie dog. *J. Mammal.* 69:236–50.
37. B. D. Chepko-Sade and Z. T. Halpin, eds. 1987. *Mammalian Dispersal Patterns.* Univ. of Chicago Press.
38. P. W. Sherman. 1989. The clitoris debate and the levels of analysis. *Animal Behav.* 37:697–98.

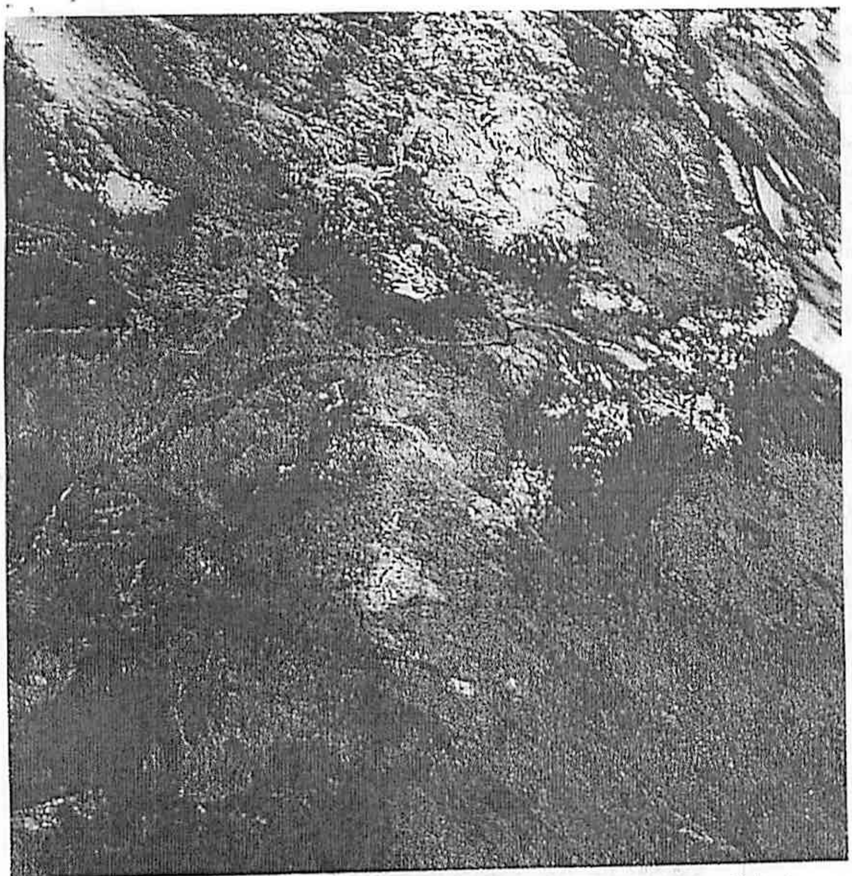

Figure 1. The Rio Grande rift is a notable geological feature of the southwestern United States, marking a region where the earth's lithosphere—the rigid outer layer made up of the crust and uppermost mantle—is being pulled apart. Flowing along the rift is one of the major American rivers, the Rio Grande. This oblique photograph taken from Skylab 4 shows the course of the Rio Grande from its source in the San Juan Mountains of southern Colorado *(top center)* through northern and central New Mexico. Visible too are ranges of the southern Rocky Mountains which partly bound the Rio Grande valley on the east. Albuquerque is located along the river just to the left of center.

deformation was a separate event from that which later gave rise to the modern grabens (fault-bounded basins) of the Basin and Range province and the Rio Grande rift (e.g., Chapin and Seager 1975; Shafiqullah et al. 1980; Eaton 1982).

A major change in plate geometry also began about 30 million years ago. At that time the trailing edge of the Farallon plate began to disappear in the subduction zone, bringing the Pacific plate directly into contact with the North American plate. Contact began at a corner of the Pacific plate, but with continued subduction the zone of contact progressively lengthened, a process which continues today. Along the zone, subduction no longer occurred; rather, the relative motion between the two plates was lateral shear (Atwater 1970), resulting in a so-called transform boundary. The San Andreas fault of California is the current expression of this boundary.

A consequence of the radical change in the nature of the plate boundary was a second period of major extensional deformation. Extension may have been induced by gaps between the plates (an unstable configuration), as subduction gave way to transform motion (Dickinson and Snyder 1979; Glazner and Bartley 1984), or by the absence of a subducted plate beneath the North American plate adjacent to the lengthening transform (Dickinson 1981). Probably also shearing forces, originating at the plate boundary but acting far inland, gave rise to a component of extension perpendicular to the plate boundary (Livaccari 1979).

Whichever mechanisms were responsible, extensional deformation began again about 20 million years ago throughout the region previously subjected to extension and volcanism. In the Rio Grande rift area, this phase of extension began about 10 million years ago. Known as the basin and range event, the process of extension gave rise to the present structure and physiography of the Basin and Range province and of the Rio Grande rift. In contrast with the preceding extensional event, basin and range deformation was not accompanied by major volcanism; instead, the lithosphere was apparently much cooler. Although extensional stresses associated with a transform boundary were the immediate cause of basin and range deformation, the earlier thermal event (part of the subduction process) may have been a necessary precondition for rifting in that it weakened an otherwise strong lithosphere.

Anatomy of the rift

The Rio Grande rift consists of a series of interconnected, asymmetrical grabens extending from central Colorado to West Texas and northern Mexico, a distance of more than 1,000 km (Fig. 4). The northern rift is a distinctive physiographic feature separating the Colorado Plateau from the Great Plains, part of the stable interior of the North American continent. The southern rift is not physiographically distinctive, yet can be distinguished from adjacent regions of the Basin and Range by a variety of geological and geophysical features, including basin size and depth (Seager and Morgan 1979; Sinno et al. 1986). The rift as a whole follows a zone of crustal weakness dating from mountain-building events millions of years before rifting. Had the lithosphere not remained weak from these events, rifting probably would not have occurred here in spite of the presence of a favorable stress field.

Individual grabens of the rift are generally bounded by steeply dipping faults or by zones several kilometers wide in which numerous steeply dipping faults are closely spaced. The dominant motion on these faults is vertical, with up to 9 km or more of offset. If the sedimentary and volcanic rocks could be stripped from the rift basins, as shown in the computer-generated view in Figure 5, this offset would dwarf the topographic relief of the Grand Canyon. In places some horizontal motion is also apparent. The full extent of lateral motion along rift faults has possibly not yet been recognized, largely because of the lack of suitable markers and detailed analysis. At depth, probably in the middle crust 10 to 20 km beneath the surface, dips of rift-bounding faults may become very shallow. In many places along the rift, low-angle faults, dating from the earlier period of extension, are exposed in the flanking uplifts. Grabens are terminated along structurally complex zones which transfer fault offsets to adjacent grabens. Adjacent grabens are typically tilted in opposite directions.

The tectonic history of the rift is recorded in its sediments, all of which are of nonmarine origin. The earliest sedimentary rocks that were deposited in the rift, mainly sandstone and conglomerate, contain a large volcanic component, indicating that the source areas lay in highlands formed during the immediately preceding volcanic event. In places, lava flows and tuffs (rocks composed of volcanic ash) are interbedded with these sediments. Many outcrops of early sediments are located high on the flanks of the rift, outside the modern grabens. Their position indicates that they were originally deposited in broad basins and were subsequently uplifted relative to the modern grabens (Stearns 1953; Chapin and Seager 1975).

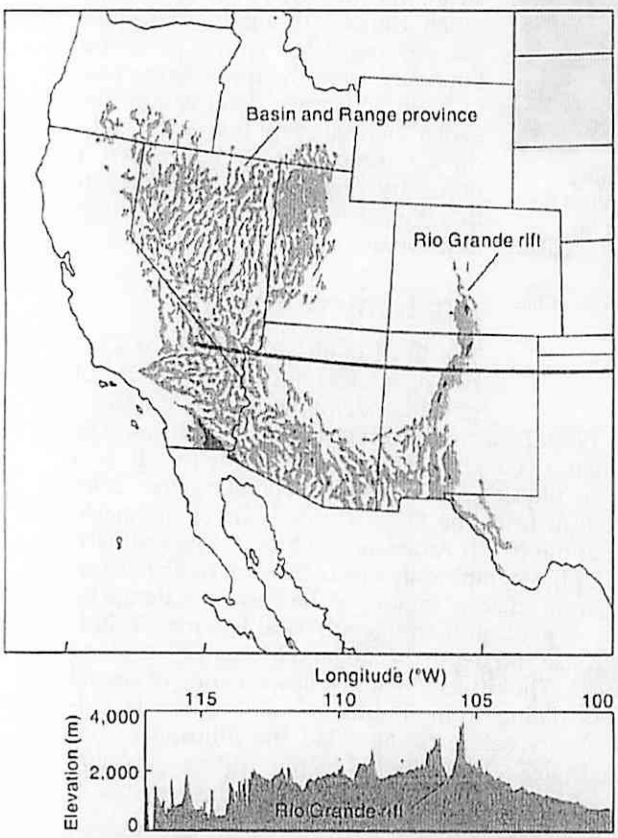

Figure 2. The physiography of the western United States betrays the effects of lithospheric extension: isolated mountain ranges and intervening valleys. Sediment-filled basins of the Basin and Range province and the Rio Grande rift are shown in yellow. Brown indicates basin depth exceeding 2,500 m. A topographic profile from 100° to 117°W, the position of which is indicated on the map, is shown below. (After King and Beikman 1974; Oppenheimer and Sumner 1980; Keller et al. 1984; Effimoff and Pinezich 1986; Gilmer et al. 1986; Harder et al. 1986; Eaton 1987.)

Overlying these early sediments is a thick sequence of conglomerate, sandstone, and mudstone comprising the main rift-filling unit, a series of formations 5 to 20 million years old named the Santa Fe Group. Rock fragments within the Santa Fe sediments are largely ancient crystalline rocks and older sedimentary rocks

The Rio Grande rift extends from central Colorado to West Texas and northern Mexico, a distance of more than 1,000 kilometers

derived from adjacent uplifted ranges of the southern Rocky Mountains. Detailed studies indicate that they were deposited in a series of topographically closed basins under conditions of intermittent flooding and desiccation. The dominant part of the Santa Fe Group consists of gravel laid down on alluvial fans which built basinward from the bounding uplifts (Cavazza 1986).

Volcanism is an important feature of continental rifts. Even though the volume of volcanic rocks associated with the Rio Grande rift is small compared with rifts such as the Kenya rift, these rocks convey unique information on thermal, chemical, and tectonic processes involved in rifting. The largest volumes were erupted in the southern part of the rift before and during the early phase of extension. This volcanism was essentially a continuation of the widespread subduction-related magmatism that preceded and accompanied extension throughout the western United States. Geochemical data indicate that this thermal event was extreme enough to begin melting the lower crust.

In the interval between periods of major extension, roughly 10 to 18 million years ago, volcanism was relatively minor and local. A recent period of magmatism began with formation of the Jemez field, a volcanic edifice constructed when about 2,000 km^3 of lava erupted along the bounding faults of the rift (Gardner and Goff 1986; see Fig. 4). About 5 million years ago, eruption of lava, mainly of basalt, became widespread throughout the rift area. For reasons not well understood, most of the eruptive activity since then has taken place not within the main grabens of the rift but rather along a narrow zone, known as the Jemez zone or lineament, that extends northeastward more than 600 km from east-central Arizona to northeastern New Mexico, oblique to the rift axis. Within the rift grabens the Jemez zone corresponds to a series of faults with recent horizontal and vertical movements (Aldrich 1986). In contrast, along most of its length outside the rift the Jemez zone does not correspond uniquely to any discernible geological features. However, it broadly demarks the boundary between extended and thinned lithosphere to the southeast, of which the rift is a part, and the core of the Colorado Plateau to the northwest.

Of the common volcanic rocks, basalt is the most important in understanding mantle processes because it

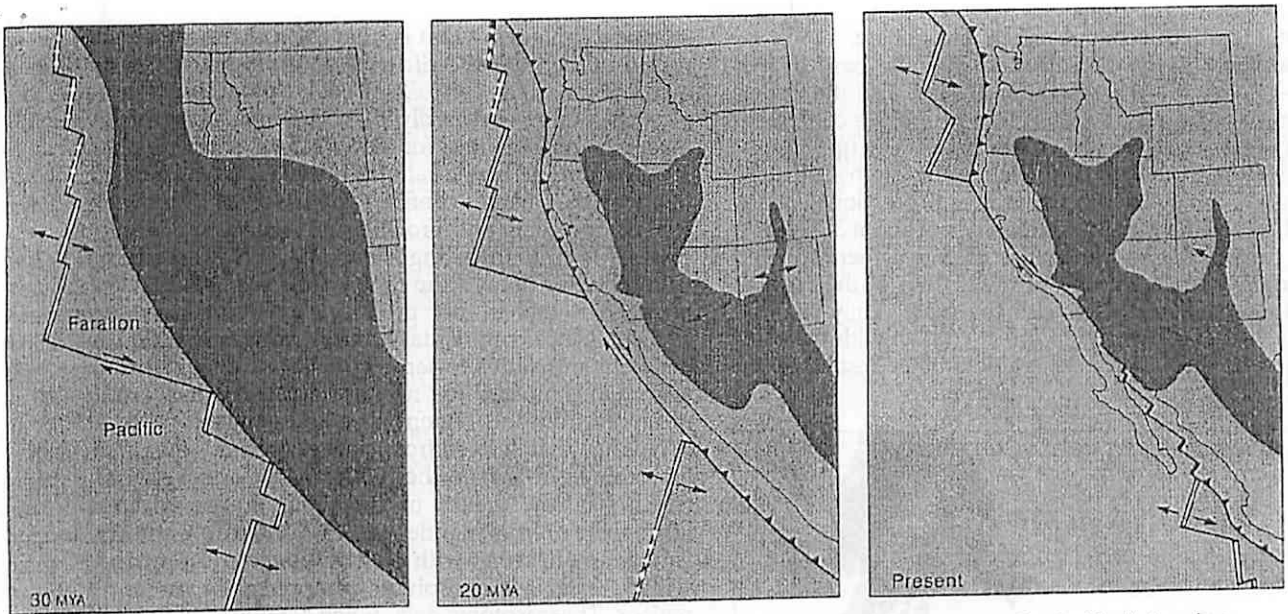

Figure 3. Plate tectonic events along the western margin of North America have caused deformation and volcanism far into the interior of the continent. Lithospheric plates are created by magmatism at midocean ridges, shown by parallel lines. Arrows show relative motions of adjacent plates. If relative motion is perpendicular to plate boundaries, one plate is forced beneath the adjacent plate at a subduction zone, shown by barbed lines. If relative motion is parallel, plates slide along boundaries at transform faults, shown by heavy lines. The shaded area in the diagram on the left shows the region of the North American plate affected by magmatism prior to 30 million years ago, when the Farallon plate was being subducted under the North American plate. A major reorganization of the plates and a change in the nature of the boundaries between them began 30 million years ago, when the Pacific plate encountered the North American plate. Subduction ceased, volcanism declined, and a new period of deformation ensued. The shaded areas in the diagrams in the middle and on the right show the region affected by extensional deformation; double-headed arrows are oriented parallel to the direction of greatest extension. (After Atwater 1970; Snyder et al. 1976; Eaton 1979; Zoback et al. 1981; Aldrich et al. 1986.)

is erupted directly from the mantle to the surface with little modification within the crust. It therefore serves as a probe of the upper mantle. Detailed chemical study of basaltic rocks shows that the main controls on their composition are the amount of melting which the mantle undergoes in yielding a basaltic melt and the depth at which this melting occurs. Small differences in the composition of the mantle sources have a secondary but significant effect on basalt, manifested mainly in the isotopic ratios of certain elements that are present in trace quantities. In addition, contamination by crustal rocks as melts migrate toward the surface creates a small but measurable shift in the composition of some basalt. The effects of crustal contamination must be subtracted from the composition of this basalt before its mantle signatures can be interpreted.

The relative concentrations of the isotopes of certain elements, for example neodymium, are not changed by melting processes and therefore are particularly sensitive indicators of different sources within the mantle. As shown in Figure 6, the ratio of ^{143}Nd to ^{144}Nd in basalt is lowest in the Great Plains, the eastern Colorado Plateau, and the northern Rio Grande rift and increases systematically to the southwest. The highest values are measured in basalt from the Basin and Range province and the southern rift. These data indicate that basalt in the region of the Rio Grande rift is derived from two compositionally distinct regions. Intermediate values of the ratio result from the tapping of different proportions of these sources (Perry et al. 1987).

Structure of the lithosphere

The crust and mantle beneath the rift are continually being modified by thinning and by intrusion of basaltic magma, resulting in lithosphere that is anomalous in many respects compared to that in adjacent, geologically stable areas. For example, the crust, which consists of layers with different physical (and, presumably, chemical) properties, is thinned beneath the rift, as shown in Figure 7. Crustal thicknesses beneath the axis of the rift range from 30 to 35 km, compared to 45 km beneath the Colorado Plateau and 50 km beneath the Great Plains. Moreover, the velocity with which seismic compressional waves travel in the lower crust is about 6% less beneath the rift than in regions adjacent to it—6.4 as opposed to 6.7 to 6.8 km/sec (Olsen et al. 1987). This small difference suggests that the rock type is similar throughout but that the velocity has been slightly decreased beneath the rift axis by higher temperatures. Thus, if it is assumed that the lower crust has a composition similar to that of andesite, a volcanic rock higher in silicon, aluminum, and alkali metals and lower in iron, magnesium, and calcium than basalt, then these velocities rule out the possibility that the lower crust beneath the rift consists largely of basaltic intrusions, as has been almost an axiom of rift models in the past. Nevertheless, there can be no doubt that some basaltic intrusions, specifically sheetlike conduits that feed surface volcanoes, are present. It should be noted that the composition and structure of the lower continental crust are currently topics of active research and debate.

Not only is mantle intruded into the base of the crust—that is, the crust is thinned—but also the upper mantle is anomalous in its physical properties compared with that under stable continental areas. The uppermost mantle beneath the rift and the southeastern Colorado Plateau is characterized by seismic compressional velocities of 7.7 to 7.8 km/sec and densities of about 3.2 g/cm^3. These values are more typical of the asthenosphere, containing a small amount of melt, than of the normal (solid) mantle directly beneath the crust. They suggest that the asthenosphere is in direct contact with the base of the crust (within the several-kilometer resolution of seismic techniques)—that is, that the asthenosphere has welled up beneath the rift, replacing normal subcrustal mantle (Sinno et al. 1986; Olsen et al. 1987). The presence of such a large, upwardly displaced mass of partially molten mantle accounts for the volcanism in the rift area.

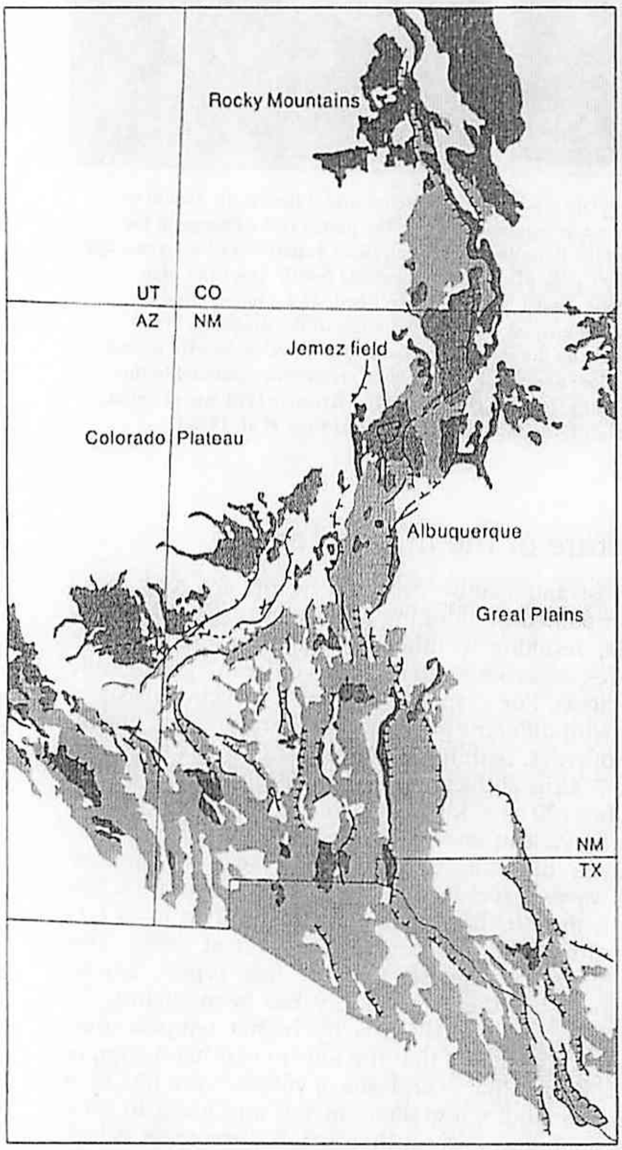

Figure 4. A closer view of the Rio Grande rift reveals the series of interconnected, asymmetrical grabens (fault-bounded basins) that divides the Colorado Plateau from the Great Plains. Sediments filling the rift are shown in yellow. Ancient (>1-billion-year-old) crystalline rocks in the cores of bounding ranges are shown in brown. Volcanic rocks younger than 15 million years are shown in pink. Black lines indicate faults, with tick marks on the downward side.

The change in the ratio of ^{143}Nd to ^{144}Nd in basalt that we noted earlier confirms the presence of asthenospheric upwelling and provides information on the processes by which upwelling may occur. ^{143}Nd is produced by radioactive decay from ^{147}Sm, whereas ^{144}Nd is nonradiogenic—that is, not produced by decay from any element. Since continental lithosphere was enriched in neodymium relative to samarium more than one billion years ago compared to "normal" asthenosphere, basalt produced from this region has a lower ratio of ^{143}Nd to ^{144}Nd than that derived from asthenosphere. Thus, alkalic basalt from the northern rift and adjacent regions, which has low values of the ratio, is derived from lithosphere or from mantle that was recently lithosphere. Farther south, basalt with high ratios records a progressively greater asthenospheric component in its source regions. These isotopic data, when combined with information (derived from abundances of major elements) about the depth where melting originates, indicate that the lithosphere beneath the rift is thin in the south and west compared to that in the north and east (Perry et al. 1987).

Moreover, by studying basalt of different ages it is possible to follow the progress of lithospheric thinning through time. Studies of basaltic rocks up to 8 million years old from a small area adjacent to the central Rio Grande rift indicate that basalt older than about 4 million years has slightly lower ratios of ^{143}Nd to ^{144}Nd ($\leq$0.51205) than younger basalt from the same area ($\geq$0.51212). This difference implies that a greater proportion of lithospheric mantle was involved in the genesis of the older basalt (Perry et al. 1988). Assuming that both the older and younger basalt was derived from equivalent depths, which seems reasonable based on its composition of major elements, these data indicate that the lithospheric mantle was thinned and replaced by asthenospheric mantle between 4 and 7 million years ago. This thinning was concurrent with the latest phase of rifting. Thus, basalt of different ages preserves a record by which the evolution of the uppermost mantle can be deciphered.

Extending the lithosphere

The composition and structure of the lithosphere beneath the Rio Grande rift raise important questions about how the lithosphere is modified during extension. For example, how much magmatic material was intruded into the lithosphere beneath the rift—that is, what percentage of the lower crust is basaltic? The amount of magma serves as a measure of the total amount of heat expended during rifting, which in turn is a constraint on convective processes in the mantle. This question is part of a broader inquiry concerning the composition and evolution of the lower crust and upper mantle worldwide.

Current interpretations of seismic data do not appear to yield compelling evidence for a large amount of basaltic rock in the lower crust beneath the Rio Grande

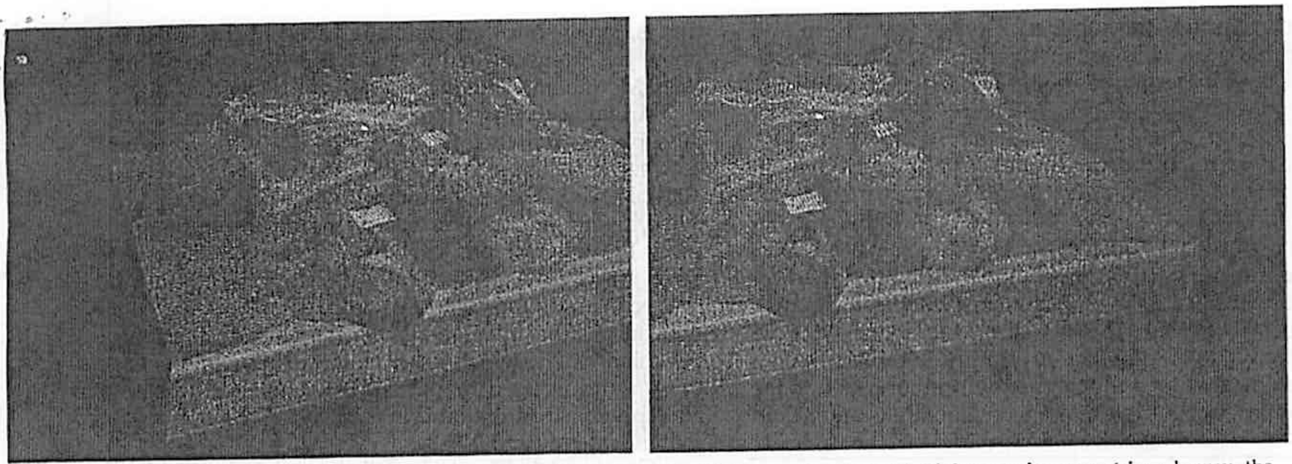

Figure 5. This computer-generated stereoscopic view shows the central part of the Rio Grande rift stripped of all sedimentary and young volcanic rocks. The view is toward the northeast. The colored surface is the top of the Precambrian basement. The black contour is sea level; colors are arbitrary elevation markers. The modern land surface is shown by parallel white lines, which intersect the Precambrian where these rocks are exposed in uplifts. The cities of Albuquerque, Santa Fe, and Los Alamos *(south to north, respectively)* are indicated by the white grids on the modern topography. This view emphasizes the large vertical offsets which the rift grabens have undergone. Comparison with Figure 1 shows that these grabens have been almost entirely filled, mainly with alluvial-fan sand and gravel. If these rocks were stripped away, the offsets would dwarf the topographical relief of the Grand Canyon.

Geologists use stereoscopic views to obtain three-dimensional images of landscapes and formations. A stereoscope can be used for this purpose, or one can train oneself to see stereoscopically by first allowing one's eyes to go out of focus so that the two parts of the view divide into four likenesses and then focusing on the single image formed as the two inner likenesses overlap. A card placed vertically on the center line can help achieve the effect. (Data from Cordell 1976; computer perspective by Melvin L. Prueitt, Los Alamos National Laboratory.)

rift. Yet interpretations of geophysical data by Okaya and Thompson (1986) and modeling of thermal and elevation data by Morgan and his colleagues (1986) suggest that the lower crust must have been thickened, presumably by intrusion of basaltic melts from the mantle, by up to 5 km in the last 5 million years in order to account for the observed high regional heat flow and elevation. How can this apparent discrepancy be resolved? There are several possible explanations.

First, basalt may be present in the lower crust as numerous thin sills (horizontal sheetlike bodies) tens to hundreds of meters thick. These sills would have little effect on seismic compressional velocities as measured by classical refraction techniques, which derive velocities from the arrival of seismic waves refracted (and reflected) by rock layers of different densities. The waves travel approximately parallel to the earth's surface and thus are not strongly affected by horizontal rock bodies. However, they would be imaged by reflection methods, which measure seismic waves reflected nearly vertically off density discontinuities below the point of observation but offer no precise means of measuring velocities. The presence of sills of contrasting mineralogy and density may explain the strong and continuous reflectors observed near the base of the crust in the central Rio Grande rift (de Voogd et al. 1988).

Second, the lower crust beneath the rift may be much more basaltic than currently assumed. Although, as we have seen, it has been widely accepted that the lower crust has a composition similar to that of andesite, recent work in other regions (e.g., Kay and Kay 1986; Griffin and O'Reilly 1987; Rudnick and Taylor 1987) suggests that it may be basaltic or at least contain a higher percentage of basalt than previously assumed. Geological interpretation of deep crustal seismic velocities (derived from field refraction measurements) requires correlating rock types with velocity values. This correlation can lead to significant uncertainty because a unique correspondence between seismic velocity and rock type does not exist. Indeed, laboratory results show a wide

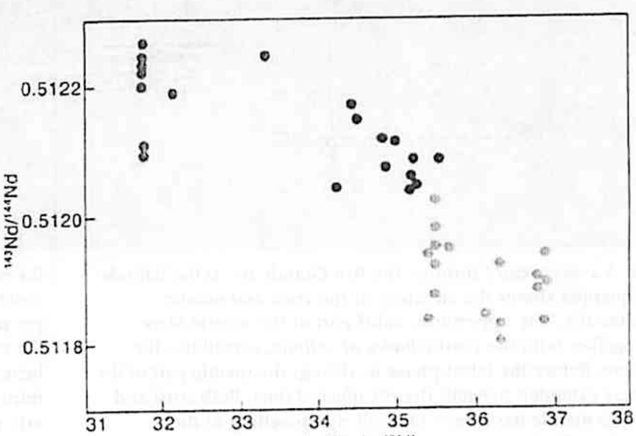

Figure 6. Information about the structure and activity of the mantle under the Rio Grande rift is provided by the volcanic rock basalt. For example, the ratio of two isotopes of neodymium—$^{143}Nd/^{144}Nd$—in basalt is a good indicator of the source of the basalt in different parts of the mantle. This graph shows ratios in alkalic basalt, which is little affected by crustal contamination, projected onto a northeast-southwest profile of the rift. Dark gray dots represent ratios in basalt from the Basin and Range province and southern Rio Grande rift; black dots represent ratios from the southeastern margin (transition zone) of the Colorado Plateau and the central rift; light gray dots represent ratios from the Great Plains, northern Rio Grande rift, and eastern Colorado Plateau. The data indicate two different sources in the mantle, as well as a mixture from them. (After Perry et al. 1988.)

range of velocities for some rock types (e.g., Kern and Richter 1981) as well as an overlap for different rock types. These uncertainties complicate precise evaluation of the petrological and mineralogical state of the lower crust.

Finally, much basaltic material may be "hidden" in the upper mantle. The upper mantle is made up of a rock called peridotite, of which the dominant mineral is olivine (magnesium orthosilicate). Typical seismic velocities of peridotite are greater than 8 km/sec. Basalt, with lower seismic velocities (7.0 to 7.2 km/sec at these depths), could possibly reduce the overall velocity to the observed values of 7.7 to 7.8 km/sec. Any of these three possibilities would allow for a much greater input of heat into the lithosphere and a high average regional elevation, and would imply that a large amount of new continental crust is formed during rifting.

If the sedimentary and volcanic rocks could be stripped from the rift basins, the offset would dwarf the topographic relief of the Grand Canyon

Another major question involves mechanisms of thinning. Ductile thinning, by which the lithosphere is stretched and displaced by the upward movement of asthenosphere, is undoubtedly an important mechanism, but it is probably not the only one. Isotopic compositions (specifically, the low ratio of ^{143}Nd to ^{144}Nd) of young basalt from the northern rift indicate that it was derived from a lithospheric mantle similar to that of the adjacent Great Plains, yet seismic and gravity data indicate that asthenosphere extends nearly to the base of the crust. This discrepancy between isotopic and geophysical signatures suggests that partial melting of the lithospheric mantle (Spohn and Schubert 1983), a process we call thermal thinning, may be an additional important mechanism. The heat required for thermal thinning may be augmented by secondary convection—that is, small-scale convection induced in the asthenosphere by extension in the overlying lithosphere (Buck 1986; Moretti and Froidevaux 1986).

An additional mechanism may be "erosion" of the lithosphere from below. Undoubtedly, the boundary between lithosphere and asthenosphere is very complex, possibly with dikes of asthenosphere intruding into the overlying lithosphere. As extension and convection proceed, the thin screens of lithospheric rock separating dikes may become detached and incorporated into the convecting asthenosphere, a process called "stoping." Erosion of lithosphere may be a small-scale version of delamination, by which subcontinental lithosphere, once broken and isolated or partially isolated from adjacent lithosphere, sinks into and is replaced by more buoyant asthenosphere (Bird 1979).

Continental rifts are usually associated with divergent plate boundaries, where they mark the breakup or incipient breakup of plates. Yet extension in the region of the Rio Grande rift began in a subduction zone environment and continues today in a transform setting. This indicates that continental rifting does not necessarily occur in a specific plate tectonic environment. A related consideration regards our terminology. The early phase of extension in what is now the Rio Grande rift, characterized by hotter lithosphere, broad basins, and low-angle faulting, did not develop the rift as we see it today. Rather, the current structural setting of the rift developed about 20 million years after the initiation of extensional deformation. Therefore, it would be more consistent with the terminology of basin and range deformation to restrict the term Rio Grande rift to the phase of narrow grabens and high-angle faults that formed about 10 million years ago in response to transform motion along the western margin of the North American plate (Baldridge et al. 1980).

Finally, rifting processes are typically described as active or passive, depending on whether "active" upwelling of asthenosphere causes the overlying lithosphere to rift or rifting is seen as a "passive" response to plate boundary forces. Because of the complex history of the Rio Grande rift, neither of these mechanisms adequately describes the evolution of the rift. Rather, it seems that

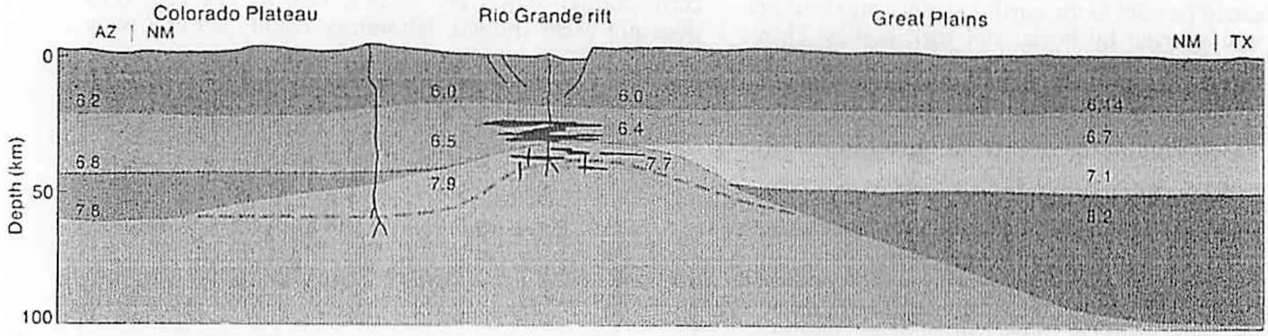

Figure 7. A cross section through the Rio Grande rift at the latitude of Albuquerque shows the structure of the crust and mantle beneath the rift. The uppermost, solid part of the mantle *(dark green)*, together with the crust *(shades of yellow)*, constitutes the lithosphere. Before the latest phase of rifting, the mantle part of the lithosphere extended beneath the rift *(dashed line)*. Both crust and lithospheric mantle have been thinned by upwelling of the asthenosphere *(light green)*, the underlying, partially molten part of the mantle. Vertical lines at the rift and to the west represent basaltic magma pushing to the surface. The velocities (in kilometers per second) with which seismic compressional waves travel through the various layers are indicated by numbers. Lower velocities beneath the rift axis are the result of higher temperatures. Possible intrusions of basaltic rock into the mantle and lower crust at the axis are shown as heavy black horizontal lines.

formation of the rift resulted from a combination of factors. Extensional forces distributed far inland, resulting first from a decreased rate of convergence during subduction and later from shear along a transform boundary (a passive process), were superimposed on a region of lithosphere that had been weakened by preexisting mountain-building and by massive and widespread magmatism. It is unlikely that formation of the Basin and Range province and the Rio Grande rift would have occurred had the lithosphere not undergone the massive heating event (possibly an active process) that immediately preceded extension. Moreover, the heating was a direct consequence of subduction, a process associated with convergent rather than divergent plate boundaries. Thus, study of the Rio Grande rift teaches us that continental rifting may result from a combination of factors, some inherited from prerift tectonic settings, operating in concert.

References

Aldrich, M. J., Jr., 1986. Tectonics of the Jemez lineament in the Jemez Mountains and Rio Grande rift. *J. Geophys. Res.* 91:1753–62.

Aldrich, M. J., Jr., C. E. Chapin, and A. W. Laughlin. 1986. Stress history and tectonic development of the Rio Grande rift, New Mexico. *J. Geophys. Res.* 91:6199–6211.

Atwater, T. 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. *GSA Bull.* 81:3513–36.

Baldridge, W. S., P. E. Damon, M. Shafiqullah, and R. J. Bridwell. 1980. Evolution of the central Rio Grande rift, New Mexico: New potassium-argon ages. *Earth Planet. Sci. Lett.* 51:309–21.

Bird, P. 1979. Continental delamination and the Colorado Plateau. *J. Geophys. Res.* 84:7561–71.

———. 1984. Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains. *Tectonics* 3:741–58.

Buck, W. R. 1986. Small-scale convection induced by passive rifting: The cause for uplift of rift shoulders. *Earth Planet. Sci. Lett.* 77:362–72.

Cavazza, W. 1986. Miocene sediment dispersal in the central Española basin, Rio Grande rift, New Mexico, U.S.A. *Sediment. Geol.* 51:119–35.

Chapin, C. E., and W. R. Seager. 1975. Evolution of the Rio Grande rift in the Socorro and Las Cruces areas. *New Mexico Geol. Soc. Guidebook* 26:297–321.

Cordell, L. 1976. Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar. *New Mexico Geol. Soc. Spec. Publ.* 6:62–70.

de Voogd, B., L. Serpa, and L. Brown. 1988. Crustal extension and magmatic processes: COCORP profiles from Death Valley and the Rio Grande rift. *GSA Bull.* 100:1550–67.

Dickinson, W. R. 1981. Plate tectonic evolution of the southern Cordillera. *Arizona Geol. Soc. Digest* 14:113–35.

Dickinson, W. R., and W. S. Snyder. 1979. Geometry of triple junctions related to San Andreas transform. *J. Geophys. Res.* 84:561–72.

Eaton, G. P. 1979. A plate-tectonic model for late Cenozoic crustal spreading in the western United States. In *Rio Grande Rift: Tectonics and Magmatism*, ed. R. E. Riecker, pp. 7–32. Am. Geophys. Union.

———. 1982. The Basin and Range province: Origin and tectonic significance. *Ann. Rev. Earth Planet. Sci.* 10:409–40.

———. 1987. Topography and origin of the Southern Rocky Mountains and Alvarado ridge. In *Continental Extensional Tectonics*, ed. M. P. Coward, J. F. Dewey, and P. L. Hancock, pp. 355–69. Geol. Soc. of London spec. publ. 28.

Effimoff, I., and A. R. Pinezich. 1986. Tertiary structural development of selected basins: Basin and Range province, northeastern Nevada. In *Extensional Tectonics of the Southwestern United States: A Perspective on Processes and Kinematics*, ed. L. Mayer, pp. 31–42. GSA spec. publ. 208.

Engebretson, D. C., A. Cox, and G. A. Thompson. 1984. Correlation of plate motions with continental tectonics: Laramide to Basin-Range. *Tectonics* 3:115–19.

Gardner, J. N., and F. Goff. 1986. Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico. *J. Geophys. Res.* 91:1763–78.

Gilmer, A. L., R. A. Mauldin, and G. R. Keller. 1986. A gravity study of the Jornada del Muerto and Palomas basins. *New Mexico Geol. Soc. Guidebook* 37:131–34.

Glazner, A. F., and J. M. Bartley. 1984. Timing and tectonic setting of Tertiary low-angle normal faulting and associated magmatism in the southwestern United States. *Tectonics* 3:385–96.

Griffin, W. L., and S. Y. O'Reilly. 1987. Is the continental Moho the crust-mantle boundary? *Geology* 15:241–44.

Harder, S. H., G. R. Keller, P. H. Daggett, and Y. A. Sinno. 1986. Cenozoic fill-thickness estimates from P-wave delays in the Jornada del Muerto and Palomas basins. *New Mexico Geol. Soc. Guidebook* 37: 135–38.

Kay, R. W., and M. Kay. 1986. Petrology and geochemistry of the lower continental crust: An overview. In *The Nature of the Lower Continental Crust*, ed. J. B. Dawson, D. A. Carswell, J. Hall, and K. H. Wedepohl, pp. 147–59. Geol. Soc. of London spec. publ. 24.

Keller, G. R., L. Cordell, G. H. Davis, W. J. Peoples, and G. White. 1984. A geophysical study of the San Luis basin. *New Mexico Geol. Soc. Guidebook* 35:51–57.

Kern, H., and A. Richter. 1981. Temperature derivatives of compressional and shear wave velocities in crustal and mantle rocks at 6 kbar confining pressure. *J. Geophys.* 49:47–56.

King, P. B., and H. M. Beikman. 1974. Geologic map of the United States. USGS.

Livaccari, R. F. 1979. Late Cenozoic tectonic evolution of the western United States. *Geology* 7:72–75.

Moretti, I., and C. Froidevaux. 1986. Thermomechanical models of active rifting. *Tectonics* 5:501–11.

Morgan, P., G. R. Keller, and W. R. Seager. 1986. Thermal and structural evolution of the southern Rio Grande rift: Geophysical and geological evidence for major Neogene plutonism. *GSA Abst.* 18:700.

Okaya, D. A., and G. A. Thompson. 1986. Involvement of deep crust in extension of Basin and Range province. In *Extensional Tectonics of the Southwestern United States: A Perspective on Processes and Kinematics*, ed. L. Mayer, pp. 15–22. GSA spec. publ. 208.

Olsen, K. H., W. S. Baldridge, and J. F. Callender. 1987. Rio Grande rift: An overview. *Tectonophysics* 143:119–39.

Oppenheimer, J. M., and J. S. Sumner. 1980. Depth-to-bedrock map, Basin and Range province, Arizona. Geophys. Lab., Univ. of Arizona.

Perry, F. V., W. S. Baldridge, and D. J. DePaolo. 1987. Role of asthenosphere and lithosphere in the genesis of late Cenozoic basaltic rocks from the Rio Grande rift and adjacent regions of the southwestern United States. *J. Geophys. Res.* 92:9193–9213.

———. 1988. Lithospheric thinning beneath the Rio Grande rift. *Nature* 332:432–34.

Rudnick, R. L., and S. R. Taylor. 1987. The composition and petrogenesis of the lower crust: A xenolith study. *J. Geophys. Res.* 92: 13981–14005.

Seager, W. R., and P. Morgan. 1979. Rio Grande rift in southern New Mexico, west Texas, and northern Chihuahua. In *Rio Grande Rift: Tectonics and Magmatism*, ed. R. E. Riecker, pp. 87–106. Am. Geophys. Union.

Shafiqullah, M., et al. 1980. K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas. *Arizona Geol. Soc. Digest* 12:201–60.

Sinno, Y. A., P. H. Daggett, G. R. Keller, P. Morgan, and S. H. Harder. 1986. Crustal structure of the southern Rio Grande rift determined from seismic refraction profiling. *J. Geophys. Res.* 91:6143–56.

Snyder, W. S., W. R. Dickinson, and M. L. Silberman. 1976. Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States. *Earth Planet. Sci. Lett.* 32:91–106.

Spohn, T., and G. Schubert. 1983. Convective thinning of the lithosphere: A mechanism for rifting and mid-plate volcanism on Earth, Venus, and Mars. *Tectonophysics* 94:67–90.

Stearns, C. E. 1953. Tertiary geology of the Galisteo-Tonque area, New Mexico. *GSA Bull.* 64:459–508.

Zoback, M. L., R. E. Anderson, and G. A. Thompson. 1981. Cainozoic evolution of the state of stress and style of tectonism of the Basin and Range province of the western United States. *Phil. Trans. Royal Soc. London* A300:407–34.

Cataclysmic Variable Stars

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On the morning of 28 April 1848, G. B. Airy, the British Astronomer Royal, received the following letter from J. R. Hind, an amateur astronomer working at a private observatory in Regent's Park: "Dear Sir, A few minutes before 1 o'clock this morning I detected a star of 6·7 or 7th magnitude, not far from Lalande 30853 (=Bessel XVI.962) which is not marked upon Wolfer's map (Berlin Charts, Hour XVI) nor previously noted by me, although this part of the heavens has repeatedly passed under examination during the present year. It is not found in the catalogues of Lalande or Bessel though each of them observed the small star above it L. 30853."

In the course of a long and successful search for new asteroids, Hind discovered a number of variable stars, that is, stars whose brightness varies over a relatively brief time. Among the many types of variable stars, novae are some of the most spectacular. The star described above turned out to be the brightest nova discovered in nearly 180 years. On the following night it reached maximum light at magnitude 4.5 and was visible to the naked eye. Many astronomers followed it over the next several months as it slowly faded. Today this nova, known as V841 Ophiuchi, is still visible as a faint blue star of magnitude 13.5.

More than a century later, looking to the south over the bright lights of central London, Hind would have stood little chance of discovering this star. In 1848, however, his discovery ignited lasting interest in the study of variable stars, so that we now know that novae such as V841 Ophiuchi are not uncommon events. Between 25 and 35 such outbursts are believed to occur within the disk of our galaxy each year. Of these, perhaps one in ten is actually discovered, usually by amateur astronomers. Only a fraction of those discovered achieve visibility with the naked eye. Since 1848, no fewer than 21 novae brighter than V841 Ophiuchi have been found (Duerbeck 1987).

What is it about the structure of these stars that causes them to undergo tremendous outbursts? How did they evolve to this state, and what will become of them? These questions can now be answered in some measure, although significant gaps in our understanding remain.

Some interacting binary stars produce explosions with an energy equal to 10,000 years' worth of the sun's output

In a typical outburst, a nova brightens by a factor of 10^4 to 10^6 (see Fig. 1), and ejects a shell of 10^{-5} to 10^{-4} solar masses of material at velocities of the order of 1,000 km/s (Gallagher and Starrfield 1978). This shell can often be resolved with a telescope some years after the outburst.

At maximum light, a nova may radiate from 10^4 to more than 10^6 times the radiant power of the sun for a few weeks or months, the duration of outburst being inversely related to the peak luminosity of the nova (at least in the visible part of the spectrum). At these luminosities, radiation pressure alone (due to photons scattered by free electrons in a stellar atmosphere) is capable of blowing matter off the surface of a solar-mass star. The total energy radiated in a single outburst is typically of the order of 10^{45} ergs, or roughly the energy output of the sun over 10,000 years, and the terminal kinetic energy of the ejecta is a number of similar magnitude.

A critical breakthrough in understanding what causes these outbursts came in 1954 with the discovery that DQ Herculis (Nova Herculis 1934) is an eclipsing binary star with an amazingly short orbital period of 4 hours 39 minutes (Walker 1954). Kraft (1963) subsequently showed that not only novae in general, but also related eruptive variables (such as the dwarf novae and nova-like variables that I discuss below) are binary systems, almost always of very short orbital period. He called these objects "cataclysmic variables," a label which has since been broadened to include various other types of exotic variable stars sharing this same binary character.

The structure of a typical cataclysmic binary is illustrated in Figure 2. A normal main-sequence star (a star supported by hydrogen burning in its core) orbits closely around a white dwarf star (a star whose nuclear fuels have been exhausted, and which is supported by electron degeneracy pressure—the pressure exerted by electrons occupying the lowest energy states possible consistent with the Pauli exclusion principle). White dwarf stars have average densities a million times greater than the sun and dimensions only about one-hundredth as large—about the size of the earth.

The two stars in a cataclysmic binary orbit so closely that tides raised on the main-sequence star by the white

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